Evaluation of PV Performance Models and Their Impact on Project Risk

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INTRODUCTION

Photovoltaic systems are often priced in \$/W_p, where W_p refers to the DC power rating of the modules at Standard Test Conditions (1000 W/m², 25 °C cell temperature) and \$ refers to the installed cost of the system. However, the true value of the system is in the energy it will produce in kWhs, not the power rating. System energy production is a function of the system design and location, the mounting configuration, the power conversion system, and the module technology, as well as the solar resource. Even if all other variables are held constant, the annual energy yield (kWh/kW_p) will vary among module technologies because of differences in response to low-light levels and temperature. Understanding energy yield is a key part of understanding system value.

System performance models are used during project development to estimate the expected output of PV systems for a given design and location. Performance modeling is normally done by the system designer/system integrator. Often, an independent engineer will also model system output during a due diligence review of a project. A variety of system performance models are available. The most commonly-used modeling tool for project development and due diligence in the United States is probably PVsyst, while those seeking a quick answer to expected energy production may use PVWatts. In this paper, we examine the variation in predicted energy output among modeling tools and users and compare that to measured output.

MODELING PROCESS

Performance modeling of a PV system is a complex process, as shown in Figure 1. The performance model, shown in the center of the figure, may be thought of as a function to which one inputs the design parameters and, drawing on databases included

with the modeling tool, the hourly and annual output of the system are calculated. In reality, all modeling tools require the user to estimate some parameters, such as soiling losses, and may ask the user to choose among data sources, such as the source of the solar resource data.

After choosing which modeling tool to use, a user may face more choices of algorithms or sub-models within the tool. For example,

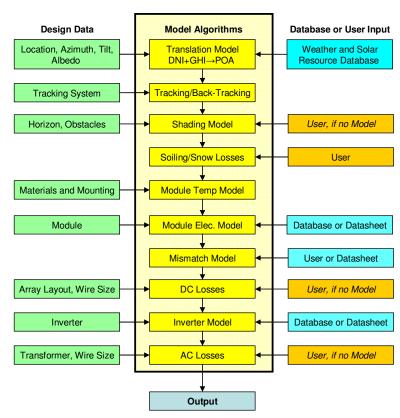


Figure 1. Performance Modeling Process

users of the System Advisor Model (SAM), formerly called the Solar Advisor Model, can choose from four models to translate solar resource data to the plane of array, three approaches to account for shading losses, three module performance models, and two inverter models. SAM users must also estimate derate factors. Even for a simple model like PVWatts, user inputs have a considerable effect on the outputs since the PVWatts user is asked to estimate system derate factor, which has a default value of 77%. These choices can lead to significantly different answers even when the same modeling tool is used, as shown below.

MODEL COMPARISON

Sandia National Laboratories hosted a PV Performance Modeling Workshop in Albuquerque, New Mexico in September, 2010 [1]. Attendees at the workshop included module manufacturers, system integrators, independent engineers, modelers and

consultants from the United States and Europe. The objective of the workshop was to review the current state-of-the-art in PV performance modeling; perform an intercomparison of available PV performance modeling tools, including comparison to measured data; and determine next steps to improve and validate model accuracy.

A unique aspect of the meeting was a pre-workshop modeling assignment. Participants were sent design descriptions of three systems along with recorded solar resource and weather data and were asked to model system performance using the model or models of their choice and return the results to Sandia for analysis before the meeting. Since recorded performance data was available for the same time period, this exercise provided a basis for discussion of model accuracy and intercomparison.

The three systems that were analyzed were a 1.4 kW mcSi and a 1.1 kW CIS system, both located in Golden Colorado; and a 1 kW cSi system located in Albuquerque. All were simple south-facing, rack-mount systems with no significant shading. For each system, participants were provided with a design description, including azimuth, tilt, inverter model information, module model and data sheet; and a TMY-2 format solar resource and weather file. The measured performance data were not provided to the modelers, so this was a blind study.

Twenty of the attendees completed the pre-workshop modeling, although no manufacturer's representatives provided their results. Seven different module performance algorithms were used, including PVsyst; PVForm, which was developed at Sandia and is used in PVWatts; PVWatts, which can be used through SAM or via the internet; the 5-parameter model from the University of Wisconsin Solar Energy Laboratory, which is available in SAM and in the California Energy Commission's PVCalculator; and the Sandia Array Performance Model (SAPM), which can be used through SAM or PVDesignPro. Two modelers used their own internal or research tools. Figure 2 shows the wide range of predicted annual energy production for one of the systems. Most of these predictions exceeded the measured results.

Two of the values obtained using PVsyst are from two individuals in the same company who calculated values for annual energy production that differed by 15%.

This difference is most likely a result of choices they made when running the model, such as the derate factors.

Uncertainty and variability in model inputs also affect results. Uncertain parameters have fixed but imperfectly known values, such as parameters related to performance (e.g. P_{mp}) and parameters related to empirical approximations (e.g. the model coefficients relating I_{mp} to irradiance).

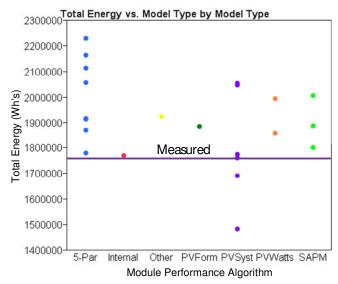


Figure 2. Results of Modeling Study

Variable parameters characterize inherently variable quantities, such as weather data. In theory, if uncertainty and variability in model inputs is quantified, the model can be exercised to produce ranges for model outputs along with probability distributions for these ranges. However, databases for model inputs generally do not provide uncertainty ranges, and most PV performance models are not structured to report the accuracy or uncertainty of output. During the workshop, the question was raised as to whether model developers could include P50 and P90 (the values of annual energy production that have a 50% or 90% probability of being met or exceeded) in the model output. Although these calculations would be possible with suitable software modifications, calculation of these values would still rely on many assumptions and choices that model users must make regarding uncertainty and variability in model inputs.

To date, little has been published on independent efforts to validate these models. Anecdotal evidence suggests that uncertainty in model inputs causes many project developers to be conservative in their performance predictions, as some observers have reported that most systems have higher than expected performance. However, experienced modelers with access to extensive data on measured system performance are able to obtain good agreement between modeled and measured output. For example, SunPower engineers monitor the performance of many of the

systems they have installed, and, using their own internal model called PVSim, have obtained good agreement between modeled and measured performance. As shown in Figure 3, predictions of annual output are within 5% of measured output across a range of systems and locations, with an average accuracy of 1.2% over predicted output.

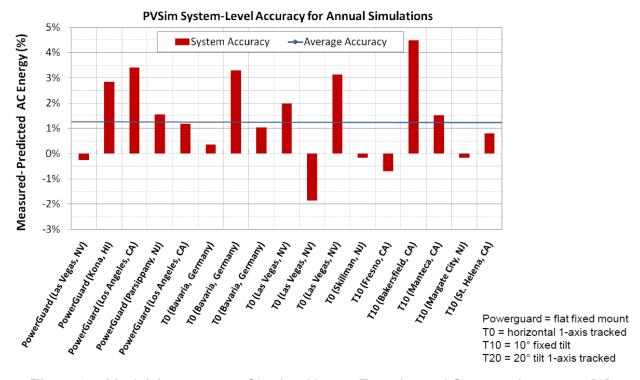


Figure 3. Model Accuracy as Obtained by an Experienced Systems Integrator [2]

PATH FORWARD

A key outcome of the PV Performance Modeling Workshop was the discussion of needs and priorities for validation and improvement of performance models. These needs fell into four areas: module data for model inputs, system data for model validation, standardized process for model validation, and desired model improvements.

Module Data: The relative performance of PV modules is important both to model users and to module manufacturers. The latter are especially concerned that models accurately differentiate the performance of their modules, such as low light level performance and efficiency as a function of temperature. In his workshop presentation [3], consultant Steve Ransome stated that independent tests have shown that kWh/kW_p

varies less than ±5% among module types, and so may be of less importance than other factors in determining project value (e.g., appearance, reliability, etc.). In any case, PV companies and project developers also need to be able to discriminate between technology choices or at least need to be able to understand the uncertainty in model results that affect these choices.

Workshop attendees were particularly concerned about the source of module data used in performance modeling. There are significant differences in the sources of module data that are used among performance models. For example, the California Energy Commission requires that data from independent laboratories be used to generate the coefficients found in their database for the 5-parameter model. PVsyst includes a database of module performance coefficients with the model. However, some manufacturers supply their customers with coefficients for PVsyst that they believe better represent the performance of their modules. The Sandia PV Array Performance Model uses performance coefficients from outdoor testing conducted at Sandia or at TÜV Rheinland Photovoltaic Testing Laboratory in Phoenix, Arizona. Key recommendations from the workshop attendees were: module testing should be performed by independent laboratories; the tests performed should generate the data required for all models, not just one specific model; multiple samples of each module should be tested; a pathway to rapidly characterize new technologies is needed; and there is a need to understand how module characteristics may change over time, beyond overall degradation of power output.

System Data: There is a critical need for high quality data sets that can be used to evaluate and improve performance models. While large system integrators that do their own monitoring have access to such data, that data is generally not available to others. It was suggested that data sets could be developed from publicly-owned projects using standardized data systems through the U.S. General Services Administration and through DOE's Solar America Cities program. A group not involved in the workshop was the performance monitoring industry, and the authors are currently reaching out to them as possible collaborators.

To meet the needs of model validation, system data needs to be high-quality and include solar resource data. The initial systems studied should be free of unusual shading, heavy soiling, and variations in orientation. Performing side-by-side evaluation of multiple technologies at one site and evaluation of like designs at multiple sites are both helpful. At a lower level of accuracy, a large number of systems are needed to evaluate performance modeling for a wide range of applications.

Standardized Process for Model Validation: A standardized process for model validation is needed to increase confidence in performance models and to improve project bankability, especially for new technologies and new companies.

Understanding and improving models as a whole may require assessing each of the algorithms shown in Figure 1. A key step is to understand which algorithms and model inputs are most critical to model accuracy, so that efforts to improve and validate models may be prioritized and focused. The authors, in collaboration with industry partners, have developed an approach based in part on residual analysis [4]. This approach was presented at the workshop. The authors also presented methods by which model sensitivity to input uncertainty may be analyzed, which would identify which model inputs and algorithms are most influential to model output. To enable model developers to provide uncertainty estimates in the model output, the uncertainty of the input data such as module coefficients must be known. Model developers and uses also need to begin participating in the standards writing process.

Model Improvements: A number of model improvements were suggested by workshop attendees. Of general interest was the ability to model multiple years by, for example, using all 30 years from which the TMY data is composed rather than just the typical year. Performing stochastic analysis using multiple years of data will illuminate the impact of weather variability on project risk. Also of general interest was the ability to model systems that may not be operating at maximum-power point because of shading or multiple array orientations. A related need is to understand and model these losses as well as mismatch losses in conventional, central inverter systems vs. systems using string-level or module-level power optimizers. Participants also stressed the need

for models to accept measured solar resource data from various instruments (e.g. only global horizontal) and in various formats. Other requested improvements included more parametric analysis, as found in SAM; the system loss output chart found in PVsyst; and output that could easily feed into a variety of financial models.

CONCLUSIONS

Developing estimates of project energy production is a key part of project development. A variety of performance models are in use, and, in the hands of the most experienced modelers, projections are obtained that compare favorably with measured energy generation. However, an informal blind study showed that participants projected a wide range of estimates of system energy production, even among those using the same modeling tools. Opportunities to improve models exist both through evaluations of the modeling algorithms and through improvements in the accuracy and uncertainty of model input data.

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^{1.} PV Performance Modeling Workshop Summary Report, Sandia National Laboratories, Albuquerque, NM, 2011. photovoltaics.sandia.gov/r e.html#PVperformance

^{2.} Ben Bourne, SunPower Corp., "Needs and Issues in Systems Performance Modeling," PV Performance Modeling Workshop, Sandia National Laboratories, Albuquerque, NM, 2011, September 22-23, 2010.

^{3.} Steve Ransome, SRCL, "Recent Studies of PV Performance Models," PV Performance Modeling Workshop, Sandia National Laboratories, Albuquerque, NM, 2011, September 22-23, 2010.

^{4.} J. S. Stein et al., "A Standardized Approach to PV Systems Performance Model Validation," Proceedings of the 35th IEEE Photovoltaics Specialists Conference, Honolulu, Hawaii, June, 2010.